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PRELIMINARY STUDY OF THE EFFECT OF UNIT REYNOLDS NUMBER ON TRANSITION SENSITIVE DATA

By

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AIR RESEARCH AND DEVELOPMENT COMMAND

US AF

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INTRODUCTION

About six years ago in the course of some work with the 1- by 1-ft. wind tunnel at the NACA Lewis Laboratory, Jack and Burgess discovered that the Reynolds number of boundary layer transition on the body they were investigating varied with stagnation pressure at constant Mach number. The variation was of significant magnitude, there being a doubling of transition Reynolds number for a four-fold increase in stagnation pressure. The reason for this was not known, but there was an inclination to blame the phenomenon on changes in tunnel flow characteristics accompanying the change in stagnation pressure. One of the present authors was privileged to see the NACA data during a visit to the Lewis Laboratory, and was able to show the same effect in transition data available from tests of cone-cylinder bodies conducted by W. R. Witt using the pressureized ballistics range at NOL. This strongly indicated that the NACA results were not entirely due to deteriorating quality of flow in the wind tunnel as pressure was lowered. As more investigators learned of these results, similar tests were conducted in a number of supersonic wind tunnels and it is now known that there is usually a marked increase in Reynolds number of transition as the unit Reynolds number, U/ν , is increased while other factors are held constant. The ratio of the free stream values of velocity and kinematic viscosity, U/ν , is dependent on stagnation pressure and temperature. It is a more general parameter than pressure, which was the variable that first led to discovery of the unit Reynolds number effect, and it has been adopted by more recent investigators. Although, to the authors' knowledge, the matter has not been investigated, one might conjecture that the same effect is present in variable density, subsonic tunnel results.

Here it should be noted that Brinich[1] has shown that unit Reynolds number, U/ν , rather than pressure or temperature alone is the controlling parameter. Therefore, we shall refer to the U/ν effect without further qualification, realizing that there may be some more general parameter not now known. We shall use the usual Reynolds number of boundary layer transition, Re_t, based on axial length from stagnation point to mean transition station although it is obviously an inadequate parameter for describing transition in any but the most limited cases. We also expect to discuss the so-called "beginning" and "end" of transition later, so no distinction will be made at this point.

It is interesting to note that discovery of this phenomena by experimental means has led to a search for clues to its existence in transition and stability theory. Brinich has demonstrated that Taylor's transition theory[2] infers

$$Re_t \propto (U/\nu)^{1/2}$$

if certain assumptions are accepted. One will recall that Taylor's theory is for subsonic flow and seems most suitable when stream turbulence exceeds roughly 0.2 percent. Laufer and Marte[3] and Laufer and Vrebalovich[4] have commented on the possible explanation of the U/ν effect by stability theory. However, no conclusive explanation of this effect has been published.

A unit Reynolds number effect apparently exists to varying degree in wind tunnel and free flight experiments, although the only clear indication of the effect in free flight known to the present authors is the data from the NOL firing range[5]. Effects produced by changing U/ν vary depending on other conditions such as body shape, but it is possible that this situation

can be met by reducing data to an effective flat plate basis. It is known that the effect may change in magnitude with stream Mach number in wind tunnel tests, though this might not be true in free flight. Changes in tunnel configuration such as insertion or removal of screens and baffles in a stilling chamber can affect the relation between transition Reynolds number, Re_t, and U/ν , as we will show later. This paper will describe the methods and early results of a continuing investigation of the effect of unit Reynolds number on transition with emphasis on the corresponding influence of this variable on measurements of other aerodynamic quantities, particularly base pressure and skin friction.

APPARATUS

The experiments described later were all conducted in Tunnel E-1 of the Gas Dynamics Facility, Arnold Engineering Development Center. Tunnel E-1 is a 12--by 12-in. intermittent supersonic tunnel. The nozzle is of the flexible-plate type and can be positioned within the nominal Mach number range of 1.3 to 5.0. Stilling chamber pressures up to 60 psia are attainable. The stagnation temperature can be varied by means of a small electric heater which is located in the stilling chamber. These experiments were conducted at nominal Mach numbers of 3.0 and 4.0. Variations in stilling chamber configuration are discussed later.

Three methods were used to detect transition, (a) schlieren, (b) hot wire, and (c) total-head probe. The hot wire and total-head probes were traversed fore and aft along the model surface. The hot wire data indicated the transition region by the change in amplitude and frequency of the velocity fluctuations. The total-head boundary layer probes were constructed by drawing a piece of .040 in. I.D. brass tubing until it tapered down to approximately

.008 in. I.D. The tubing was then honed to a wall thickness of about .003 in. and flattened to approximately .005 in. x .010 in. at the probe tip.

MODELS

The transition surveys were all made on a 20-caliber tangent ogive-cylinder model, 18 inches in length and 1-inch in diameter. With the exception of a 1/2-inch aluminum piece for the nose tip, this model was constructed of nylon. Nylon was used because of its high specific heat and low rate of heat conductivity in an attempt to maintain a near constant model temperature during a brief blow. The base pressure models consisted of three 20 caliber tangent ogive-cylinder models of 1 in. diameter, with lengths of 8, 12, and 18 inches. A highly finished surface was obtained on all models, the surface roughness being about 8-10 rms microinches.

RESULTS AND DISCUSSION

Preliminary Analysis

This work was inspired by the need to find a parameter that would enable the correlation of base pressure data, particularly for the case of entirely laminar boundary layer flow on an aerodynamic body. The base pressure, normalized by the free-stream static pressure to form the base pressure ratio, p_b/p_∞ is used throughout this paper. This ratio is ordinarily presented as a function of a Reynolds number based on total axial length of the test body. We shall refer to this as the length Reynolds number and denote it by the symbol Re_L. There are methods for generalizing

base pressure data when the boundary layer becomes turbulent on the body, this being the easier problem due to the negligible variation of base pressure ratio after the length Reynolds number, Re_L, exceeds the transition Reynolds number, Re_t. Chapman[6] has dealt with this case in detail. However, there is great variation of base pressure ratio with Reynolds number when transition occurs in the wake, so attention was confined to this condition. Figure 1 illustrates the typical curve of p_b/p_∞ as a function of the length Reynolds number, Re_L. We are not presently concerned with the right side of the picture for reasons already given. The far left side represents a region of very low Reynolds numbers not normally encountered in the usual supersonic tunnel test of a slender missile. Also, it is thought that the peak of the curve marks the downstream limit of transition in the separated flow, and after transition passes downstream of the wake closure, its location should not be of primary importance in determining base pressure. Kavanau[7] has discussed this case and presented experimental data for the very low Reynolds number range. Thus, it is the middle region of Fig. 1 that is of present concern.

Crocco and Lees[8] state that the rapid decline of p_b/p_∞ with increasing length Reynolds number in the region of interest is partly due to upstream movement of boundary layer transition along the separation zone. This is accompanied by an increasing mixing rate which enables the separated flow to support lower base pressures. The present authors reasoned that data of such "transition sensitive" nature would be influenced by unit Reynolds number if measured under conditions where Re_t, the transition Reynolds number, varied with unit Reynolds number, U/ν. Therefore, the length Reynolds number, Re_L, could not be a satisfactory parameter for correlating base pressure data in this case. It would seem better to use some quantity

related to the location of transition, although this means that transition location as a function of U/ν must be known. In this regard, it should be remarked that Chapman, Kuehn, and Larson[9] recently published results of an extensive investigation of separated flows wherein they show the importance of transition location in connection with several separated, two-dimensional flows. In fact, the parameter to be introduced in this paper could be deduced from their results or an earlier report[10] by the same authors. However the origin of the present work is closer to the paper by Crocco and Lees. The latter authors also regard the decrease of boundary layer thickness with increasing Reynolds number as partly responsible for the variation in base pressure ratio. Although this may well be true, data used by the present authors show little dependence of base pressure ratio on boundary layer thickness, but great dependence on transition location.

In testing the new base pressure parameter attention was confined to shapes having long cylindrical afterbodies at zero angles of attack such that local pressures are very near free stream values just upstream of the bases. Then, since there are practical difficulties associated with the measurement of distance to transition when transition occurs in the wake, distances x_t and x_{tb} were defined as on Fig. 2. All actual measurements of x_t were taken when transition occurred on the test bodies, and x_t on the hypothetical extension was obtained by an extrapolation of x_t vs U/ν. The new base pressure parameter was then written as x_{tb}/D, it being thought that the diameter, D, is the appropriate scaling or non-dimensionalizing quantity to use here. This parameter represents the distance from model base to mean transition location on a hypothetical extension of the body and must take into account the effect of unit Reynolds number. Although, the justification for assuming that the trend of x_t with U/ν continues

unchanged after U/ν becomes low enough for transition to occur in the wake may be dubious, results obtained thus far seem to support this procedure.

Transition Measurements

Base pressure data were available from tests of two models consisting of 20-caliber tangent ogive noses followed by right cylindrical afterbodies of different lengths, so it was only necessary to determine x_{tb} as a function of U/ν for conditions corresponding to the base pressure data. In order to correspond to the base pressure models, the transition data were taken with an ogive-cylinder body similar to the older base pressure models except for greater length of afterbody.

Inasmuch as the tunnel air supply was being shared with another facility during these experiments, it was not possible to control stagnation temperature. Thus, model wall-to-ambient temperature ratios varied and transition was affected accordingly. These preliminary results do not include any correction for variable boundary layer heating conditions.

Figure 3 shows a typical hot wire trace and a corresponding schlieren indication. It appears that the first indication of turbulence in the hot wire output corresponds to a body station appreciably ahead of the station that would be identified in schlieren pictures. This was true throughout our experiments, and it was found that the x_t shown by schlieren consistently averaged 25% more than the first indication from the hot wire traces. From inspection of the hot wire traces, it seems that the beginning of "fuzziness" seen on schlieren photographs corresponds to the location where the hot wire shows fully developed turbulence. Considering the relative sensitivity of these two methods for detecting transition. this result does not seem surprising. Unfortunately the full transition region was never explored by pitot probe during these experiments, but the "beginning" of transition as indicated by the minimum in a curve of total head vs. body

station was found to be just slightly downstream of the beginning of turbulence as interpreted on the hot wire traces, e.g., Fig. 4. However, there are only two hot wire data points on Fig. 4, so this conclusion is tentative.

Although there are straight lines through the data points on Fig. 4, it is not certain that no curvature exists. On the other hand, the straight lines fit reasonably well over the entire range of U/ν values explored, so they were used for subsequent determinations of x_{tb}. Figures 5 and 6 present the transition measurements for $M_\infty = 3.98$. Figure 7 summarizes the transition data in terms of Re_t and U/ν . Only the upper or schlieren determined curves of Figs. 4-6 are represented on Fig. 7. The subsequent analysis is based on transition locations as indicated by schlieren photographs rather than the "early indication" curves drawn from the hot wire data. Justification for this procedure rests largely on the seemingly consistent response of transition sensitive quantities such as base pressure and skin friction to the transition indications of the schlieren photographs. The reason for this is tentatively thought to be due to lag between initial unsteadiness or amplification of disturbances and the larger degree of turbulence required to affect transition sensitive measurements. We are not now inclined to call the transition locations seen in schlieren photographs the "end" of transition. Indeed, it seems that such locations correspond more closely to what is often called the "beginning" in the sense that skin friction data begin a more rapid trend toward the turbulent level at Reynolds numbers corresponding to transition as seen by schlieren. The skin friction data points presented later in this paper begin to depart from the theoretical laminar curve at a Reynolds number corresponding to initial unsteadiness seen in the hot wire trace, but the major break away does not occur until a Reynolds number corresponding to the schlieren determined

transition station is attained. The curves on Fig. 7 are of the form

$$Re_t = \text{const.}\ (U/\nu)^n$$

which seems to be the case for similar data taken by others.

It is interesting to note the effect of changes in stilling chamber configuration. Tunnel E-1 has a conventional, large stilling chamber with more than the usual number of screens and baffles. In addition, there is a smaller, inner stilling chamber just ahead of the wind tunnel nozzle. This is a tubular section, heavily blocked by baffles and screens which may be removed to leave only the open tube, or the entire inner chamber including tubular shell may be removed. Thus there are three main configurations possible, although the complete inner stilling chamber is not used at the lower Mach numbers. Figure 7 shows the effect of the inner stilling chamber insofar as Re_t is concerned. An effect consistently noted in the hot wire records for $M_\infty = 3.98$ was the appearance of turbulent bursts in the boundary layer when the inner chamber was installed. These bursts were not seen when the inner chamber was removed. However, the inner chamber yielded higher transition Reynolds numbers. A possible explanation may be based on the qualitative nature of the hot wire work. A highly developed instrument was not used, and it is possible that the frequency range did not include all the significant frequencies. Therefore, turbulent bursts may have been present in both cases but only captured by the hot wire in one case. These bursts can also be seen on the schlieren photographs when the inner stilling chamber is being used.

Noteworthy too is the behavior of a model having a relatively large single roughness element in the form of a trip wire on the nose. Values of Re_t are lower and the trend with U/ν is more gradual, but the effect

is entirely similar. It seems likely that the trip wire would lose its effectiveness as very low values of U/ν are reached since boundary layer thickness would then become very large compared to wire diameter. Therefore, the curve for the model with trip wire should become coincident with the smooth model as U/ν decreases.

Base Pressure Correlation

Base pressures were measured on the family of ogive-cylinder models at two Mach numbers and with several wind tunnel stilling chamber configurations that effectively changed turbulence level in the stream. Figures 8 and 9 show these data as well as some other data from Kurzweg.[11] The latter data are presented because they were obtained with a wind tunnel having atmospheric supply pressure and Re_L was varied by changing length of afterbody on the cone-cylinder models. There should be no U/ν effect under such circumstances, but boundary layer characteristics were varied by the changing lengths so the data provide another means for checking the new base pressure parameter. One notices immediately that the data on Figs. 8 and 9 are not correlated by the usual parameter, Re_L.

Figures 10 and 11 show the same data plotted against x_{tb}/D for all $x_{tb} \gtrsim 0$. The fine degree of correlation is all the more remarkable when it is realized that the entire spread of points at $x_{tb}/D = 0$ corresponds to $\pm$ 1/4 inch error in x_t location. The abscissas of Figs. 10 and 11 were computed from the faired curves of Re_t vs U/ν . It is clear that base pressure is mainly responsive to transition location when transition occursβ in the separated wake. Any variation in base pressure ratio imposed by varying boundary layer profiles or other possible factors is apparently insignificant compared to transition location in the case of separation zone transition.

The appearance of body diameter, D, in the base pressure parameter implies that pressure at the base of a large diameter body will be lower than at the base of a smaller diameter body when x_{tb} is the same. This may seem improbable to some, but available evidence supports this conclusion. Holder and Gadd[12] suggested Reynolds number based on body diameter as a base pressure parameter, thus recognizing the importance of diameter. However this diameter Reynolds number is not adequate to correlate all data. Figure 12 illustrates what may happen if a prototype and a scale model with identical x_t vs (U/ν) characteristics are tested. At equal values of x_{tb}/D, values of p_b/p_∞ will be equal but U/ν for the prototype has to be considerably different from the corresponding value for the scale model when x_{tb}/D ratios are equal. Thus Re_L will, in general, be much different.

Effect on Skin Friction Measurements

Turning now to a discussion of the possible influence of unit Reynolds number on skin friction measurements, the major point to be made here is that the transitional skin friction curve may be steep or shallow according to the variation of Re_t with (U/ν).

Referring to Fig. 13, it is clear that the relationship between Re_L and Re_t for a given model will generally vary with U/ν in the manner shown when a variable density tunnel is used. Hence, measurements within the transitional region are accompanied by varying Re_t values. Point (1) on Fig. 13 corresponds to the case $Re_L = Re_t$. Point (3) corresponds to a measurement made when Re_t remains constant, i.e., Re_t same as at point (1). Point (2) corresponds to a measurement made with a greater Re_t value, namely $(Re_t)_B$, and hence a lesser area of turbulent flow on the model or

a lower overall skin friction coefficient. Since most of the available turbulent skin friction data are usually converted to fully turbulent values by analytical procedures after being measured in the transitional region, this is an important observation. It can be seen that one is essentially jumping from curve to curve in the transition region if U/ν is varying. When U/ν is constant, as was the case when the data on Fig. 14 were measured, a rather steep transitional curve is obtained. On the other hand, if Re_t increases with U/ν and U/ν is increasing, a very shallow transitional curve may be measured, e.g., Fig. 15.

CONCLUDING REMARKS

The basic importance of the relative location of transition for transition sensitive data has been shown. It is disturbing to contemplate the implications of the unit Reynolds number effect relative to the many wind tunnel tests which involve transition sensitive data. We see that similarity of model geometry and equal Reynolds numbers by no means guarantee equal results. For transition sensitive data, equal results between free-flight and wind-tunnel tests will require the duplication of the relative location of transition.

In order to present transition sensitive data in generalized form, it seems necessary to determine the dependence of x_t on U/ν at the same time the primary experiment is being conducted. Since different body shapes will, in general, produce different x_t vs U/ν curves, correlation of transition sensitive data from widely differing bodies or different wind tunnels is difficult without direct experimental measurement of transition locations for the range of unit Reynolds numbers covered. The seriousness of the situation can best be judged by comparison of x_t vs U/ν curves

obtained for different shapes and different wind tunnels, but it does not seem likely that there is an easy way to avoid the extra work if a correlation of data is desired. The need for data from other wind tunnels concerning the effect of unit Reynolds number is apparent.

In one sense, it is fortunate that base pressures are dominated by a single variable, namely the relative location of transition, when transition occurs in the separation zone. The sensitivity of the base pressure ratio to the precise location of transition should be noted. The rate of change of the base pressure ratio with x_{tb}/D is relatively large for transition near the model base. For example, for the models of this investigation there was a 30 percent increase in base pressure ratio for a movement of one-inch of the relative transition location.

To conclude, the authors wish to thank the personnel of GDF who assisted in the completion of the work described.

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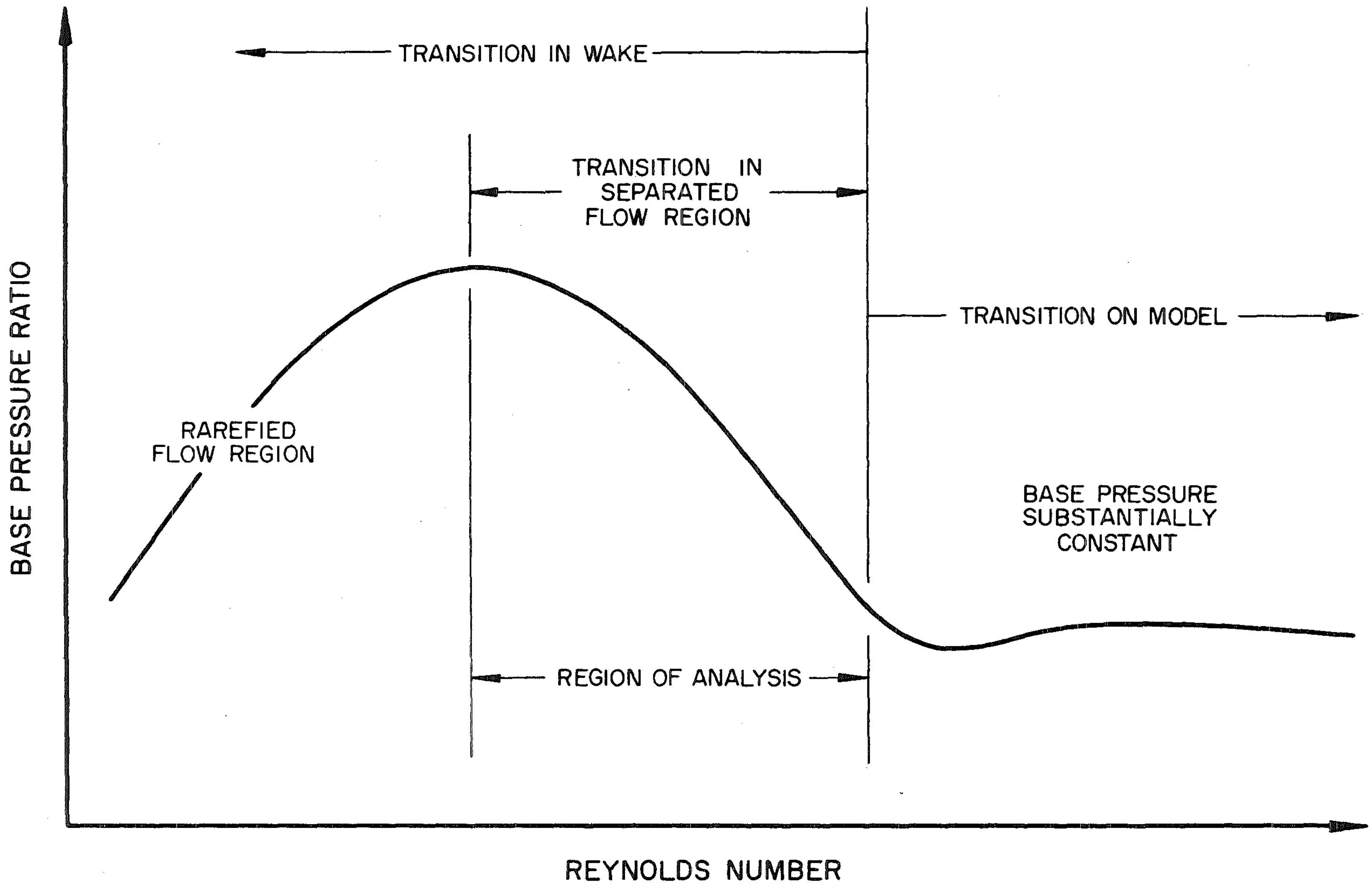


TRANSITION IN WAKE
TRANSITION IN SEPARATED FLOW REGION
TRANSITION ON MODEL
RAREFIED FLOW REGION
BASE PRESSURE SUBSTANTIALLY CONSTANT
REGION OF ANALYSIS
BASE PRESSURE RATIO
REYNOLDS NUMBER

FIGURE 1

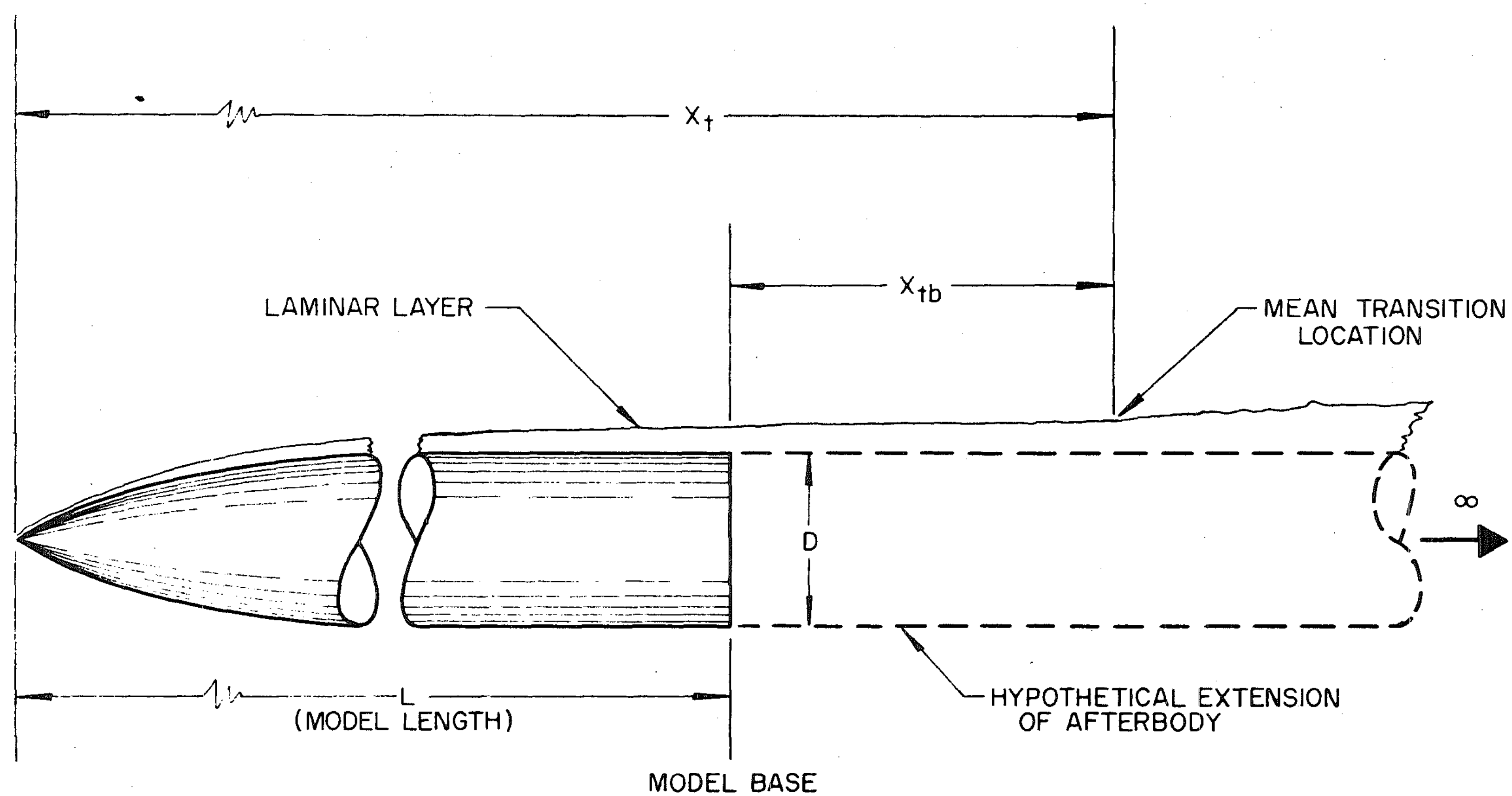
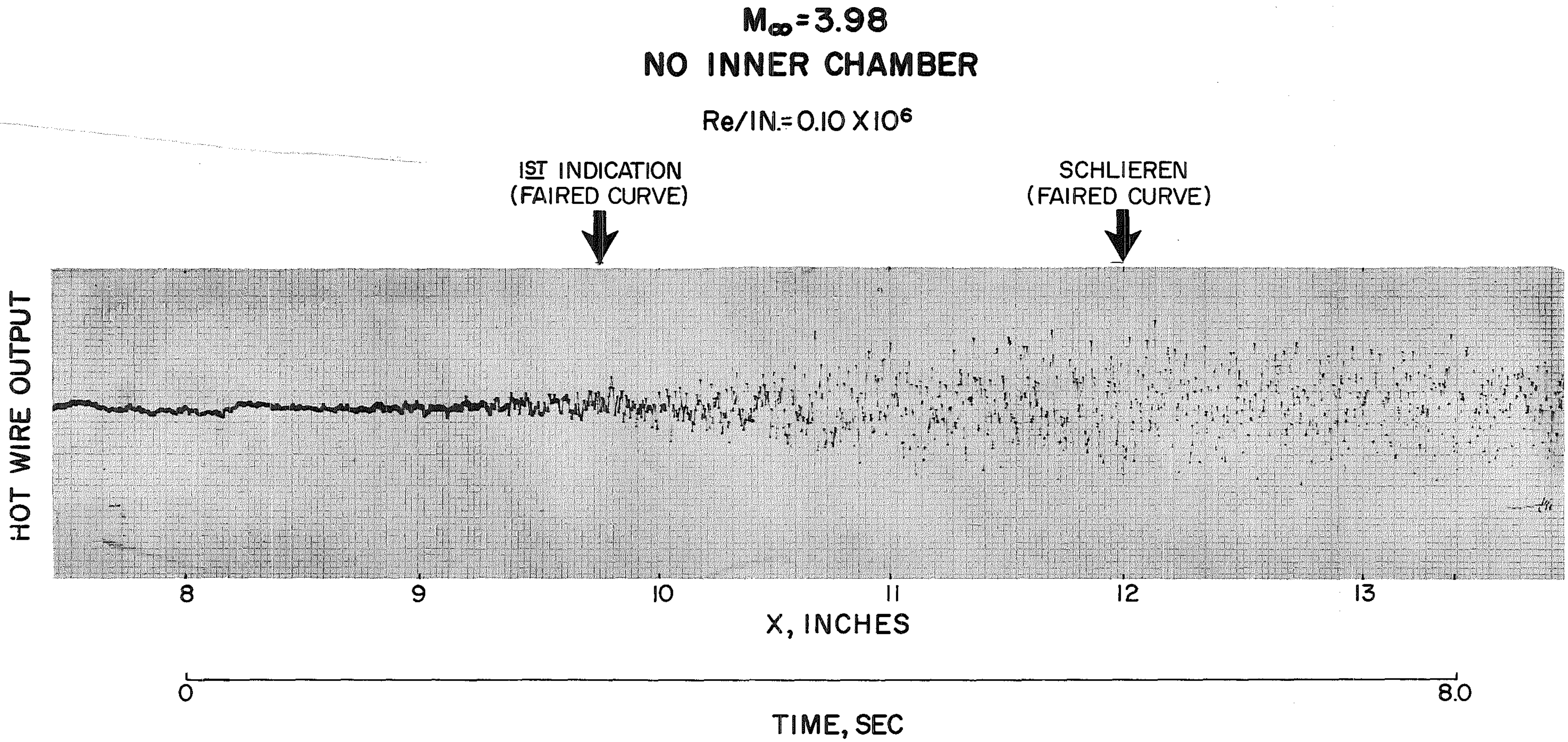

X_t
X_{tb}
LAMINAR LAYER
MEAN TRANSITION LOCATION
D
∞
L
(MODEL LENGTH)
HYPOTHETICAL EXTENSION OF AFTERBODY
MODEL BASE

FIGURE 2



$M_\infty = 3.98$
NO INNER CHAMBER
Re/IN. = 0.10 X 10^6
1ST INDICATION (FAIRED CURVE)
SCHLIEREN (FAIRED CURVE)
HOT WIRE OUTPUT
8
9
10
11
12
13
X, INCHES
0
8.0
TIME, SEC

FIGURE 3

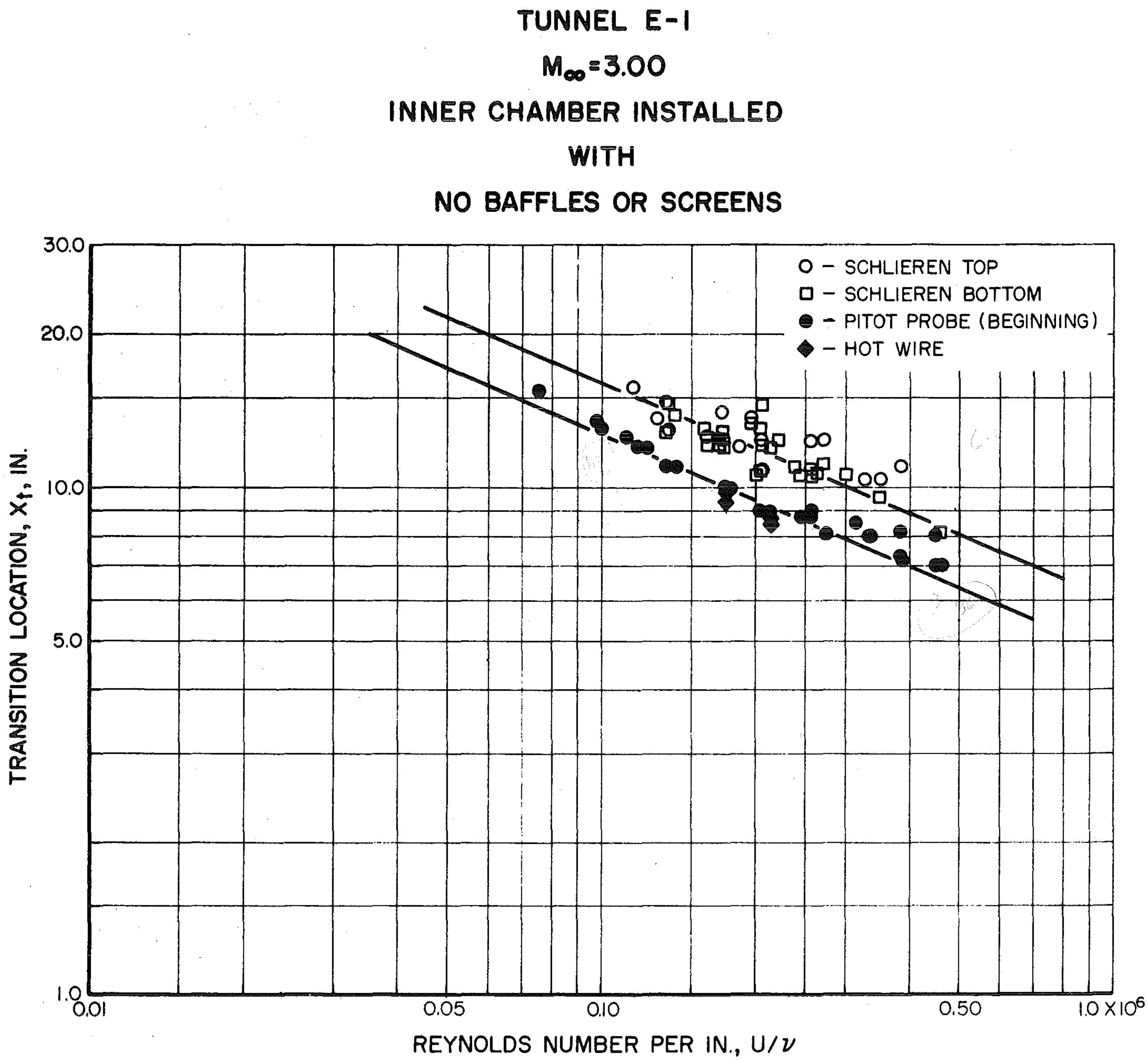

TUNNEL E-1
$M_\infty = 3.00$
INNER CHAMBER INSTALLED
WITH
NO BAFFLES OR SCREENS
○ – SCHLIEREN TOP
□ – SCHLIEREN BOTTOM
● – PITOT PROBE (BEGINNING)
◆ – HOT WIRE
30.0
20.0
10.0
5.0
1.0
TRANSITION LOCATION, X_t, IN.
0.01
0.05
0.10
0.50
1.0×10^6
REYNOLDS NUMBER PER IN., U/ν

FIGURE 4

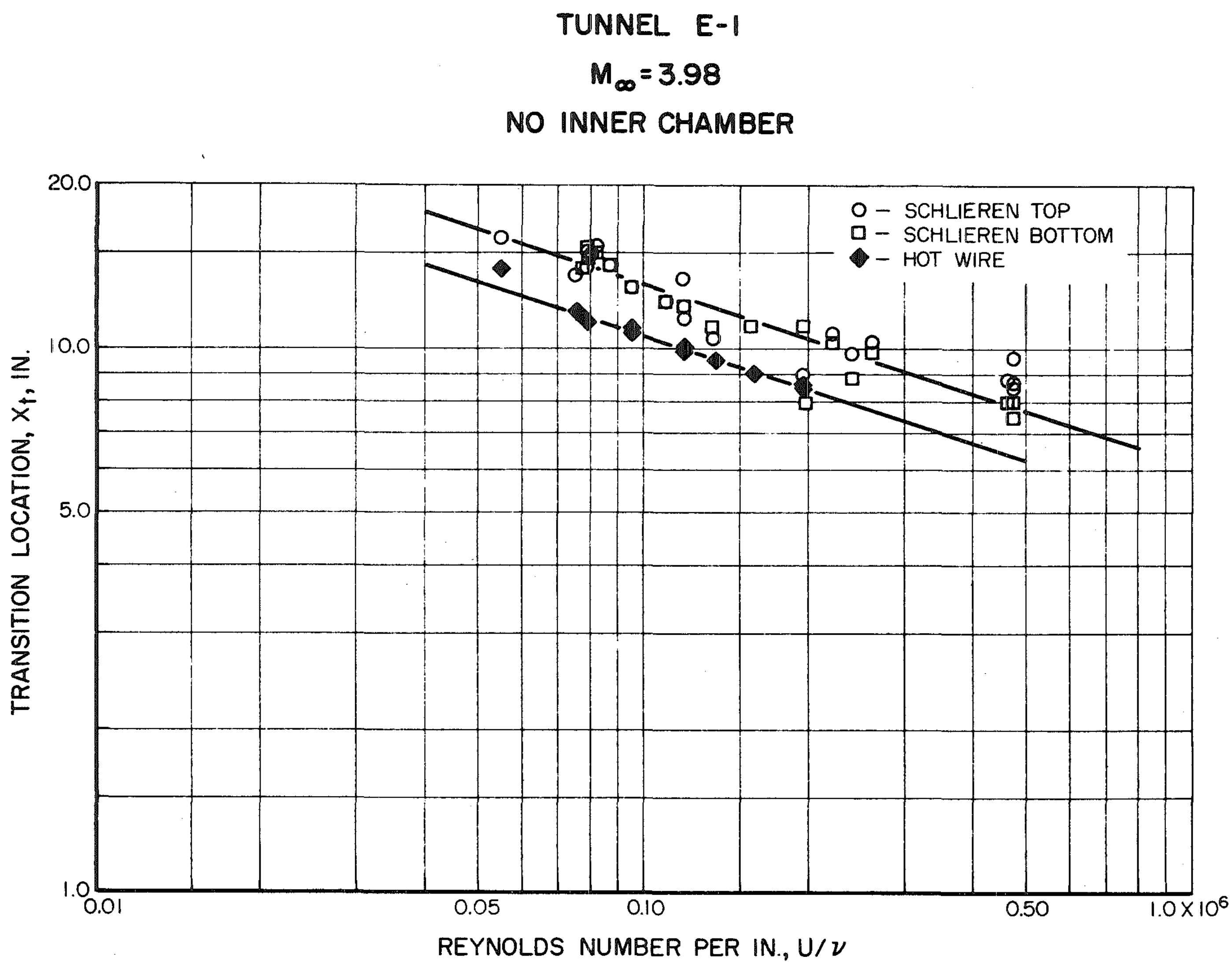

TUNNEL E-1
$M_\infty = 3.98$
NO INNER CHAMBER
○ – SCHLIEREN TOP
□ – SCHLIEREN BOTTOM
◆ – HOT WIRE
20.0
10.0
5.0
1.0
0.01
0.05
0.10
0.50
1.0 X 10^6
TRANSITION LOCATION, X_t, IN.
REYNOLDS NUMBER PER IN., U/ν

FIGURE 5

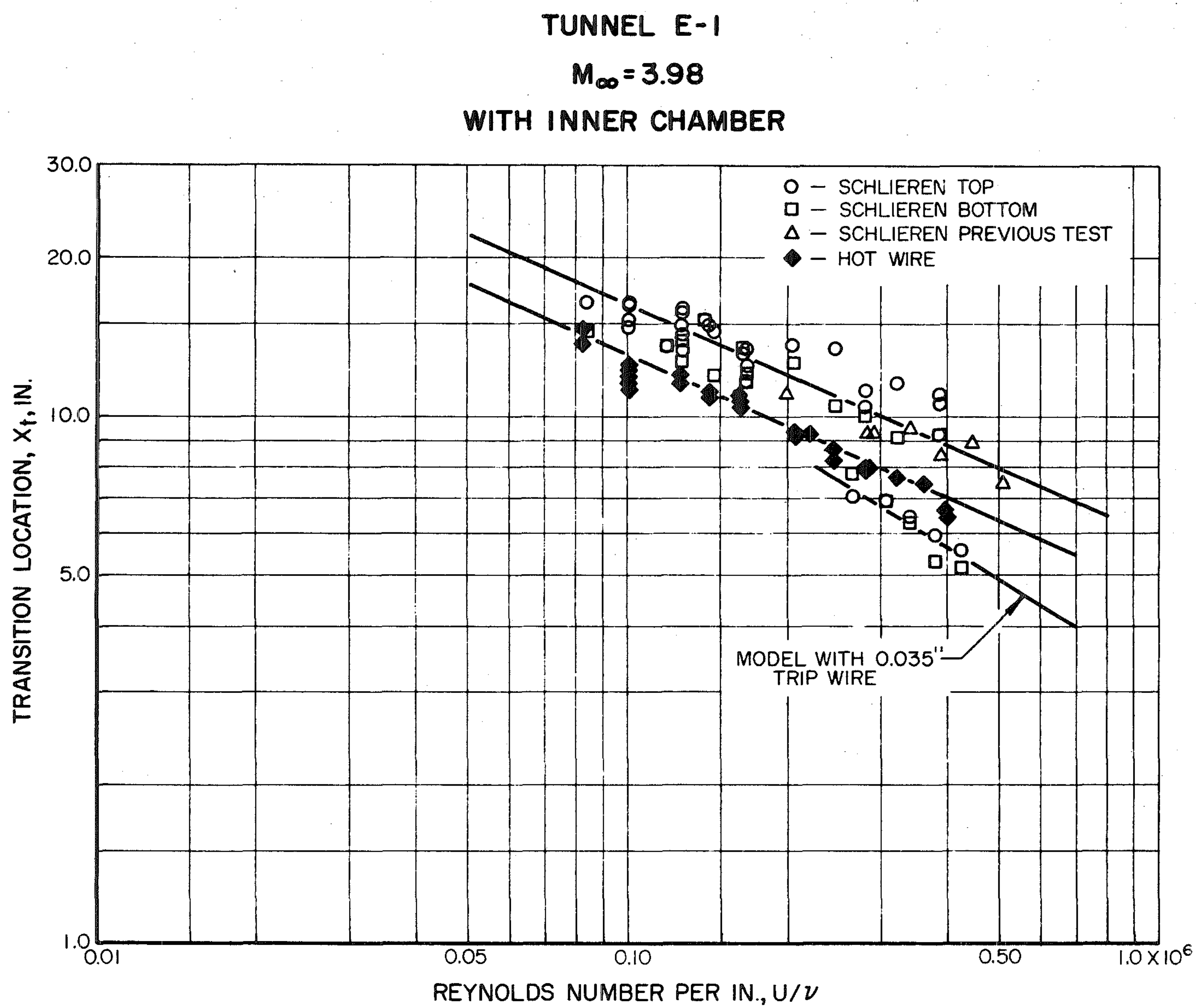

TUNNEL E-1
$M_\infty = 3.98$
WITH INNER CHAMBER
O — SCHLIEREN TOP
□ — SCHLIEREN BOTTOM
△ — SCHLIEREN PREVIOUS TEST
◆ — HOT WIRE
MODEL WITH 0.035" TRIP WIRE
TRANSITION LOCATION, X_t, IN.
REYNOLDS NUMBER PER IN., U/ν
30.0
20.0
10.0
5.0
1.0
0.01
0.05
0.10
0.50
1.0×10^6

FIGURE 6

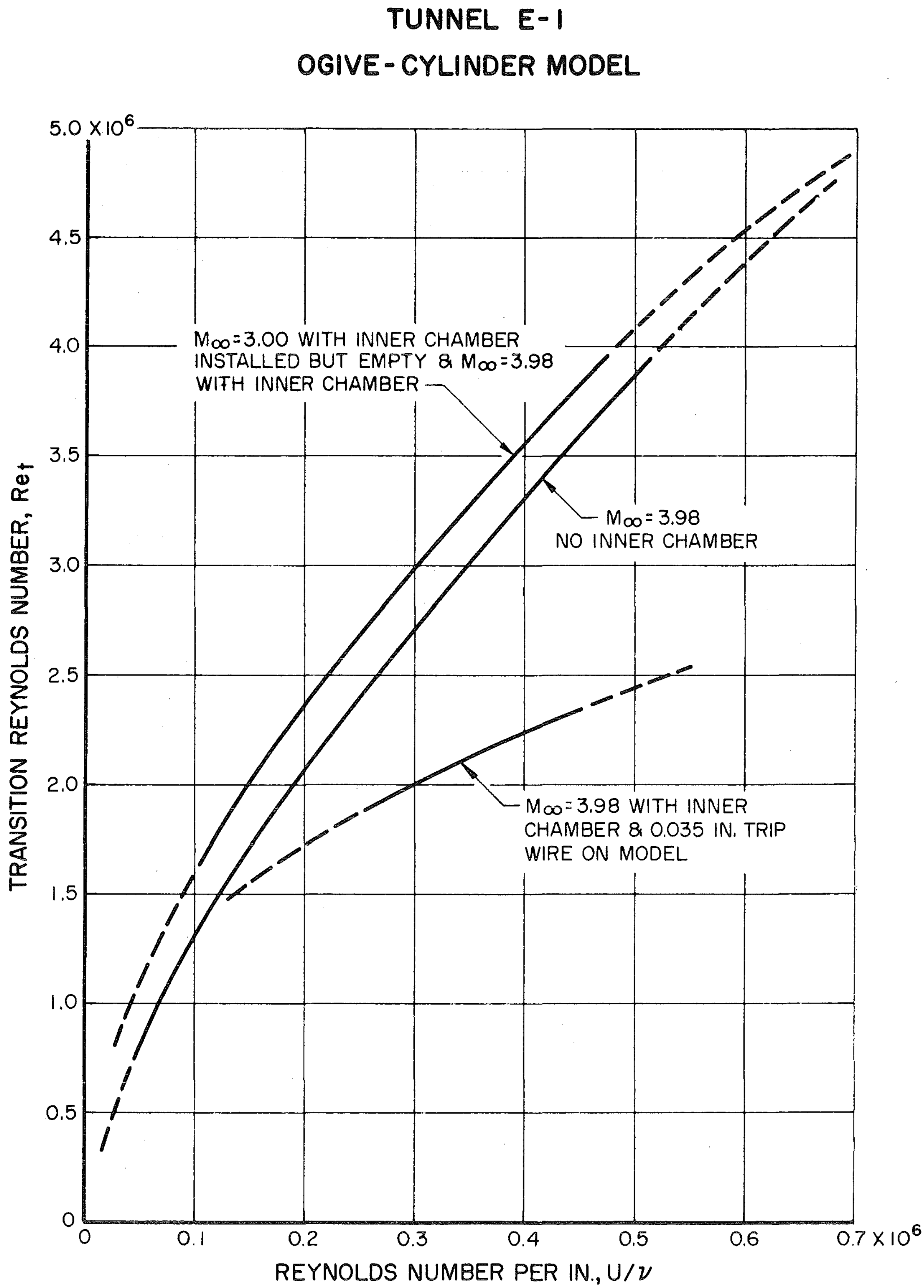
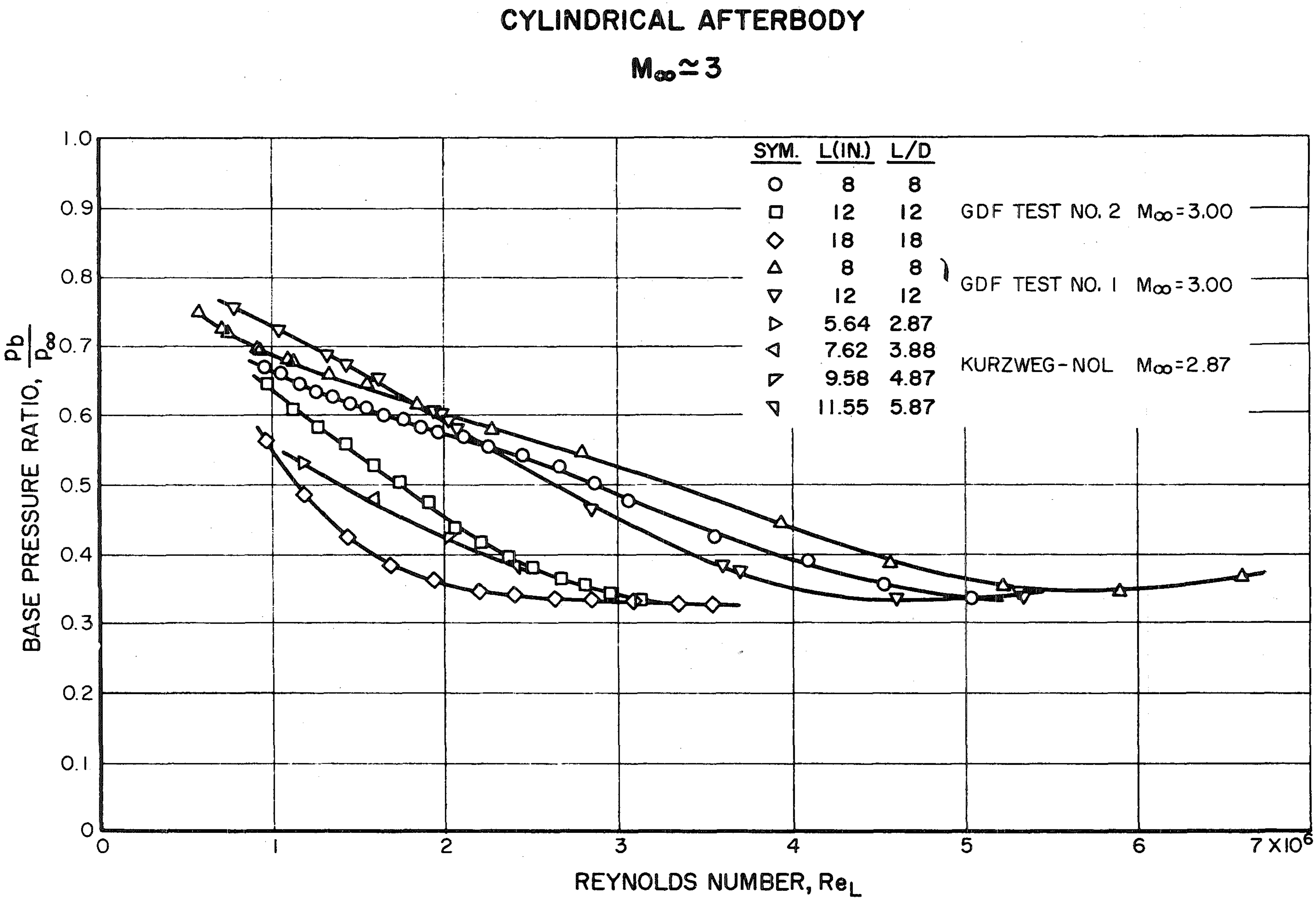

TUNNEL E-1
OGIVE-CYLINDER MODEL
5.0 X 10^6
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
TRANSITION REYNOLDS NUMBER, Re_t
M_∞=3.00 WITH INNER CHAMBER INSTALLED BUT EMPTY & M_∞=3.98 WITH INNER CHAMBER
M_∞=3.98 NO INNER CHAMBER
M_∞=3.98 WITH INNER CHAMBER & 0.035 IN. TRIP WIRE ON MODEL
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7 X 10^6
REYNOLDS NUMBER PER IN., U/ν

FIGURE 7



CYLINDRICAL AFTERBODY
M∞ ≃ 3
SYM. L(IN.) L/D
○ 8 8
□ 12 12 GDF TEST NO. 2 M∞=3.00
◇ 18 18
△ 8 8
▽ 12 12 GDF TEST NO. 1 M∞=3.00
▷ 5.64 2.87
◁ 7.62 3.88
9.58 4.87 KURZWEG-NOL M∞=2.87
11.55 5.87
BASE PRESSURE RATIO, pb/p∞
REYNOLDS NUMBER, ReL
0 1 2 3 4 5 6 7 X10^6
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

FIGURE 8

CYLINDRICAL AFTERBODY

$M_\infty \simeq 4$

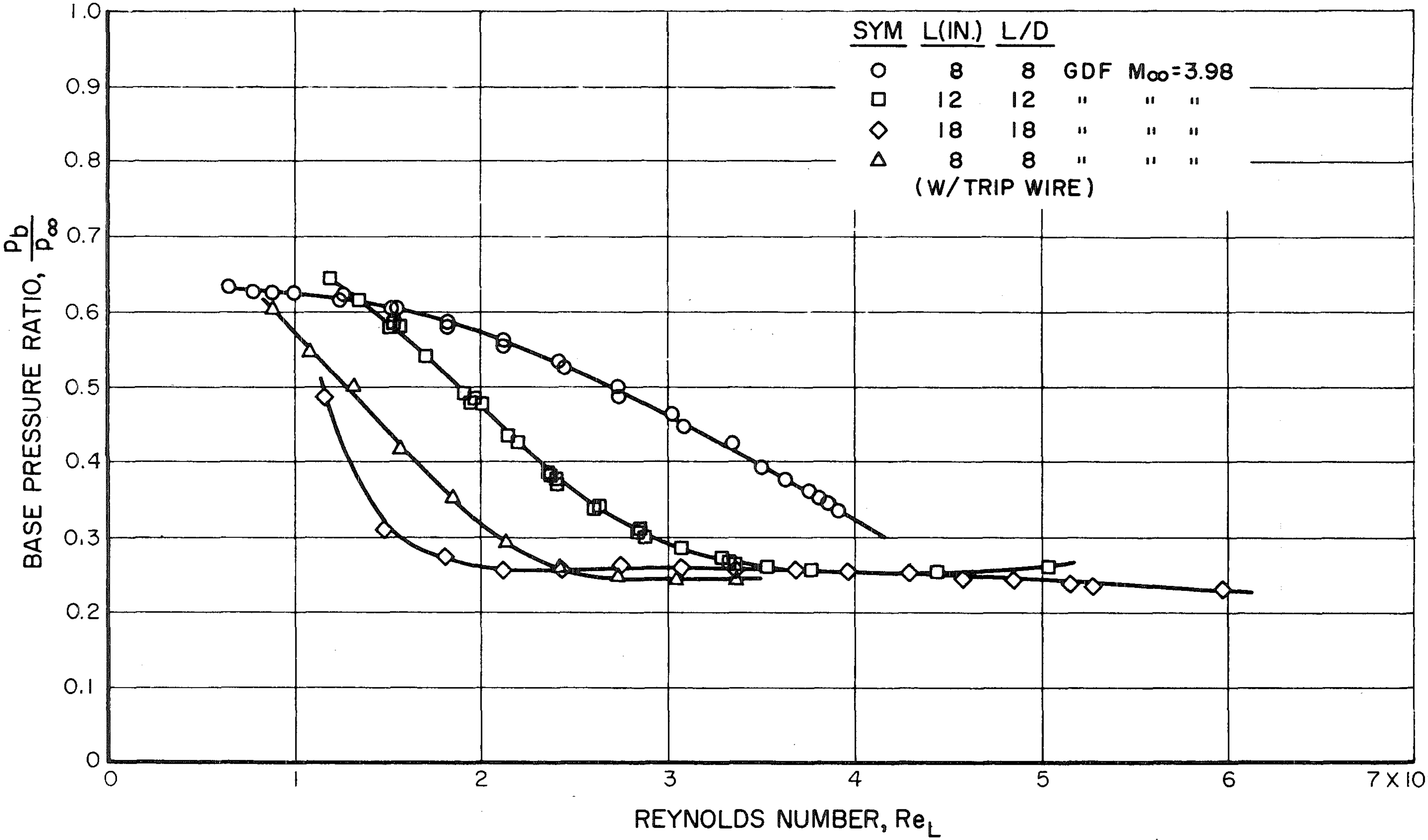
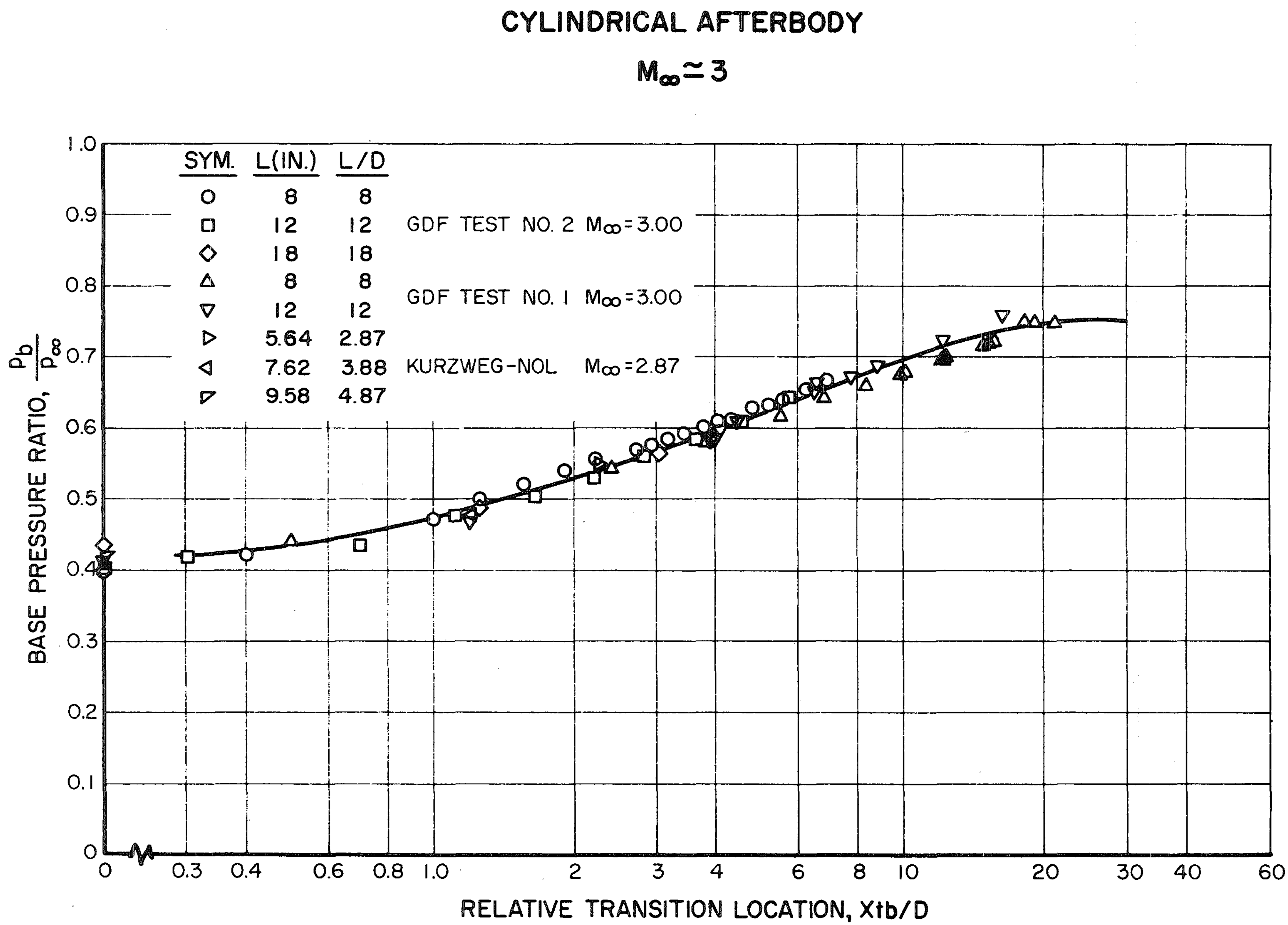
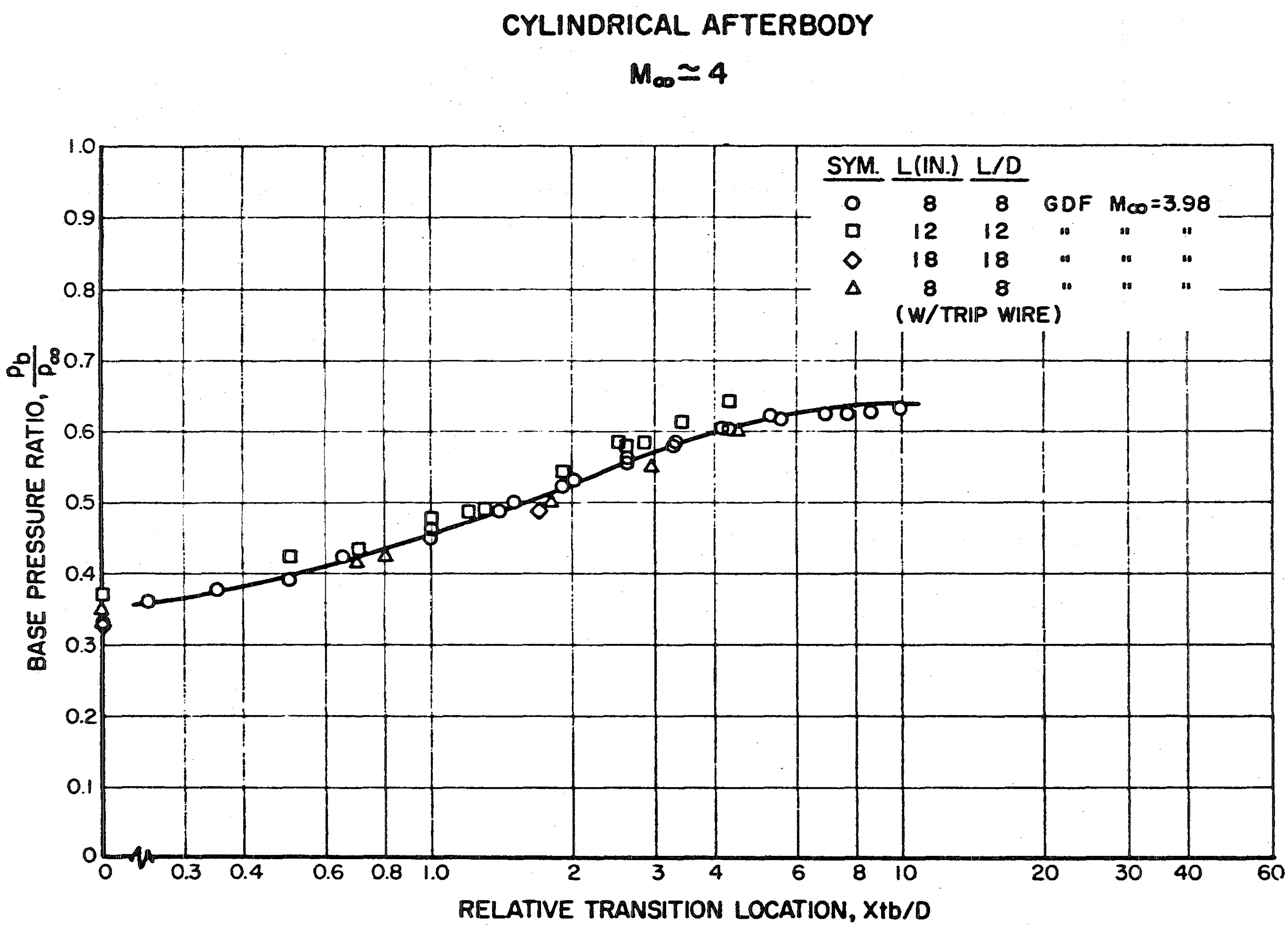


FIGURE 9



CYLINDRICAL AFTERBODY
$M_\infty \simeq 3$
SYM.
L(IN.)
L/D
8 8
12 12
18 18
8 8
12 12
5.64 2.87
7.62 3.88
9.58 4.87
GDF TEST NO. 2 M_∞=3.00
GDF TEST NO. 1 M_∞=3.00
KURZWEG-NOL M_∞=2.87
BASE PRESSURE RATIO, $\frac{p_b}{p_\infty}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.3
0.4
0.6
0.8
1.0
2
3
4
6
8
10
20
30
40
60
RELATIVE TRANSITION LOCATION, Xtb/D

FIGURE 10



CYLINDRICAL AFTERBODY
M∞ ≃ 4
SYM. L(IN.) L/D
8 8 GDF M∞=3.98
12 12 " " "
18 18 " " "
8 8 " " "
(W/TRIP WIRE)
BASE PRESSURE RATIO, pb/p∞
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.3 0.4 0.6 0.8 1.0 2 3 4 6 8 10 20 30 40 60
RELATIVE TRANSITION LOCATION, Xtb/D

FIGURE 11

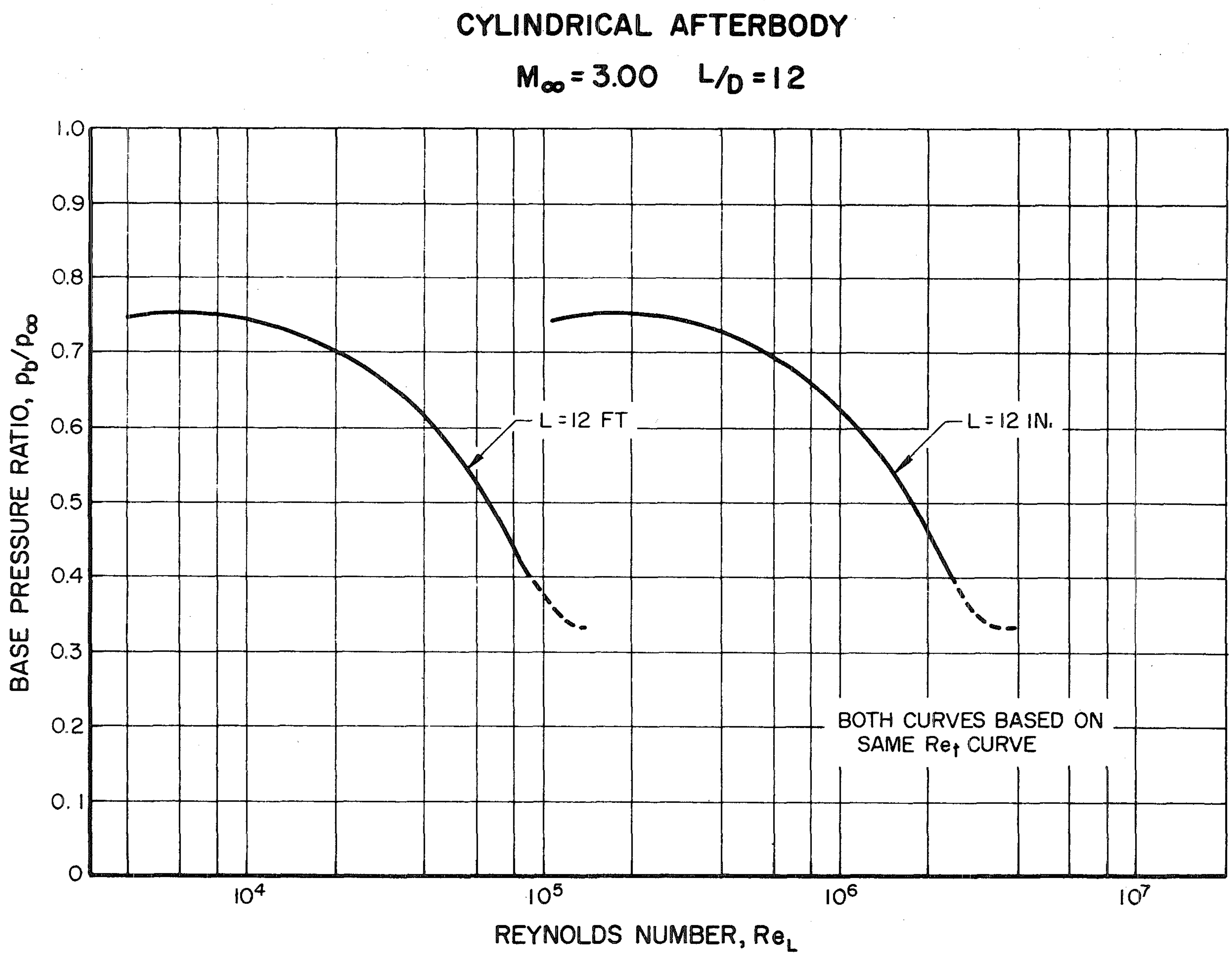
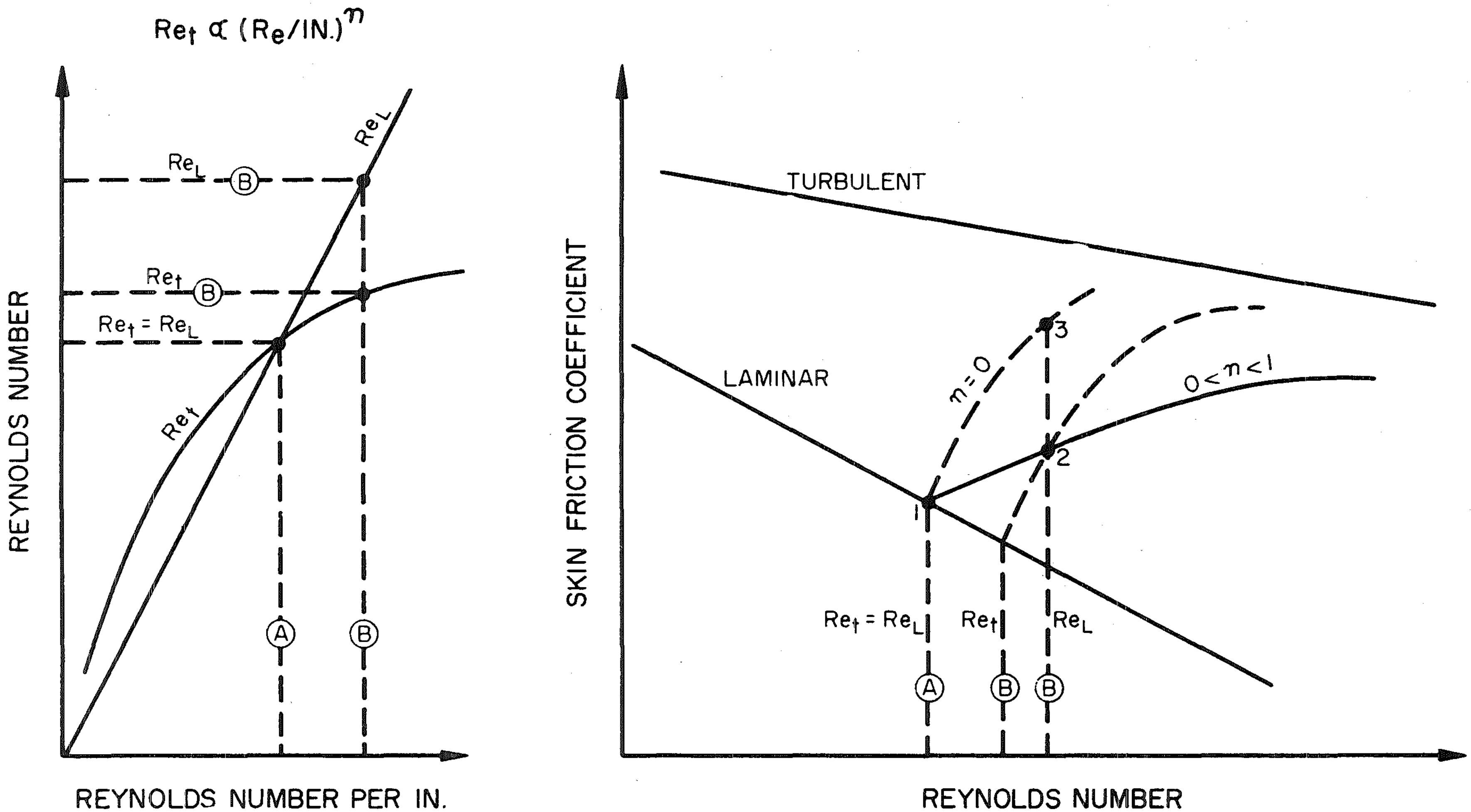
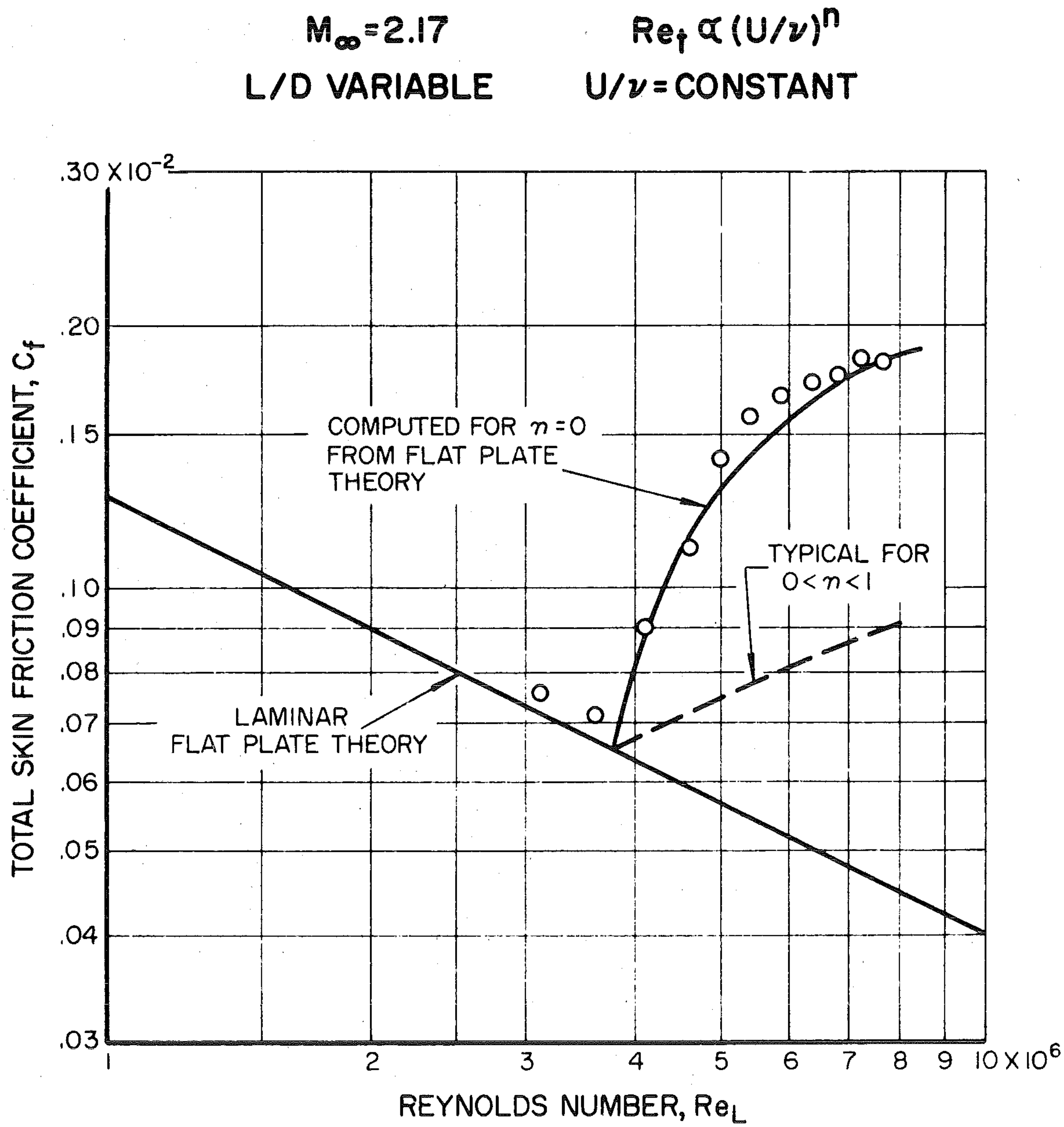

CYLINDRICAL AFTERBODY
$M_\infty = 3.00 \quad L/D = 12$
BASE PRESSURE RATIO, p_b/p_∞
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
L = 12 FT
L = 12 IN.
BOTH CURVES BASED ON
SAME Re_t CURVE
10^4
10^5
10^6
10^7
REYNOLDS NUMBER, Re_L

FIGURE 12



Ret ∝ (Re/IN.)^n
REYNOLDS NUMBER
ReL
ReL Ⓑ
Ret Ⓑ
Ret = ReL
Ret
Ⓐ
Ⓑ
REYNOLDS NUMBER PER IN.
SKIN FRICTION COEFFICIENT
TURBULENT
LAMINAR
n=0
0<n<1
1
2
3
Ret = ReL
Ret
ReL
Ⓐ
Ⓑ
Ⓑ
REYNOLDS NUMBER

FIGURE 13



$M_\infty = 2.17$
L/D VARIABLE
$Re_t \propto (U/\nu)^n$
U/ν = CONSTANT
.30 X 10⁻²
.20
.15
.10
.09
.08
.07
.06
.05
.04
.03
TOTAL SKIN FRICTION COEFFICIENT, C_f
1
2
3
4
5
6
7
8
9
10 X 10⁶
REYNOLDS NUMBER, Re_L
COMPUTED FOR $n = 0$ FROM FLAT PLATE THEORY
TYPICAL FOR $0 < n < 1$
LAMINAR FLAT PLATE THEORY

FIGURE 14

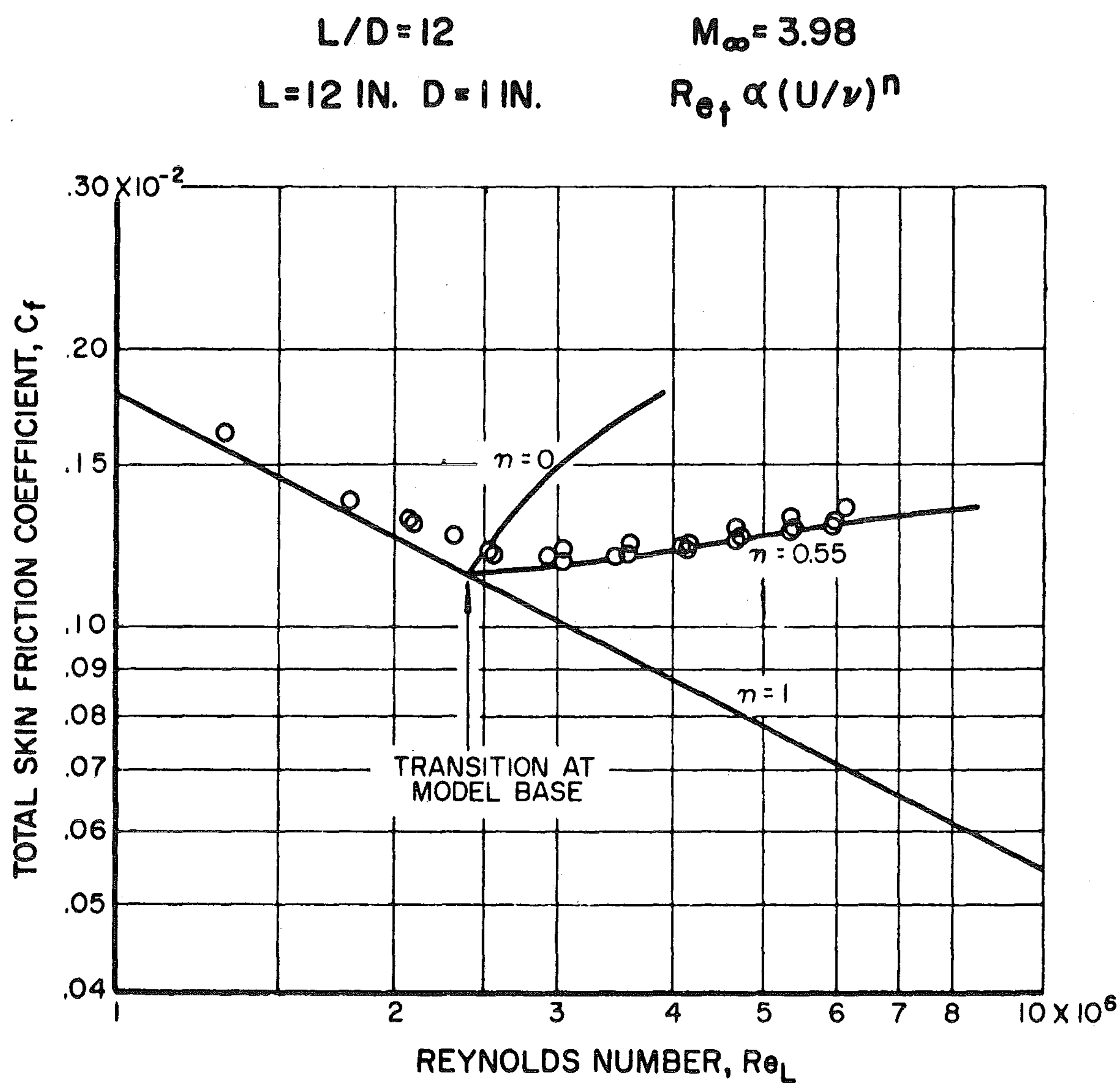

L/D = 12
L = 12 IN. D = 1 IN.
$M_\infty = 3.98$
$R_{e_t} \propto (U/\nu)^n$
TOTAL SKIN FRICTION COEFFICIENT, C_f
.30 X 10^{-2}
.20
.15
.10
.09
.08
.07
.06
.05
.04
$n = 0$
$n = 0.55$
$n = 1$
TRANSITION AT MODEL BASE
1
2
3
4
5
6
7
8
10 X 10^6
REYNOLDS NUMBER, Re_L

FIGURE 15